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Dynamics and Vibroacoustics of Machines (DVM2014)

# Hydraulic bipedal robots locomotion mathematical modeling

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**Abstract**

The paper delivered describes a new approach into kinematics and dynamics of the robots with a tree-like kinematic structure based on the elements of graph theory. Block-matrix equation for robot's movement within generalized coordinates is valid for different tree-like kinematic structures with no change in tracing. It permits to develop generalized software for the whole class of tree-like kinematic structure. Some of the modelling details in hydraulic actuator of bipedal robot are submitted. Experimental research data of robot's walking based on mathematical modelling are compared to those of a pilot model.
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*Keywords:* Bipedal robot; partitioned matrix representation of dynamics; electro hydraulic servo valve

## 1. Introduction

The key priority in development of anthropomorphic robots is set upon developing control algorithm of robotic mechanism in term of dynamics and power efficiency [1].

The mechanisms of robotics dummy and bipedal robot (BR "DSHR") (fig. 1), equipped with electro-hydraulic drives have been developed and produced at the BMSTU department of «Hydromechanics, Hydromachines and Hydro-Pneumoautomatics» for experimental research of theirs motion.

DSHR mechanism has twelve degrees of freedom, all equipped with the Electro-Hydraulic Servo Drives (EHSD). Robot's height is 2.2 m and its mass is 220 kg. DSHR is equipped with a body angle stabilizing system that works according to robot's predetermined mechanical trajectory and controlled torques between the foot and a support surface.

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It is a difficult task to submit DSHR as a simplified mechanical model to meet existing analytical synthesis methods in manipulation which provide stable robot's walking and are relevant to a real DSHR mechanism equipped with the EHSD [2].

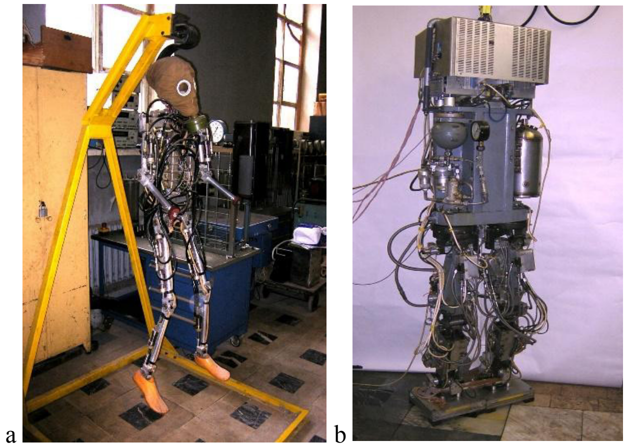


Fig. 1. (a) robotic dummy; (b) bipedal robot "DSHR" (BMSTU).

Additional research into DSHR movement on a valid mathematical model of mechanism is to be carried out to correct the obtained manipulation principles.

## 2. Block-matrix notation motion equations of the treelike kinematical structure mechanism

DSHR kinematic block diagram is shown in fig.2. The concept of the virtual rack is introduced at DSHR kinematical structure for some inertial space point and robot's body connection. Even without robot's hands its kinematical structure has become a branched one [3].

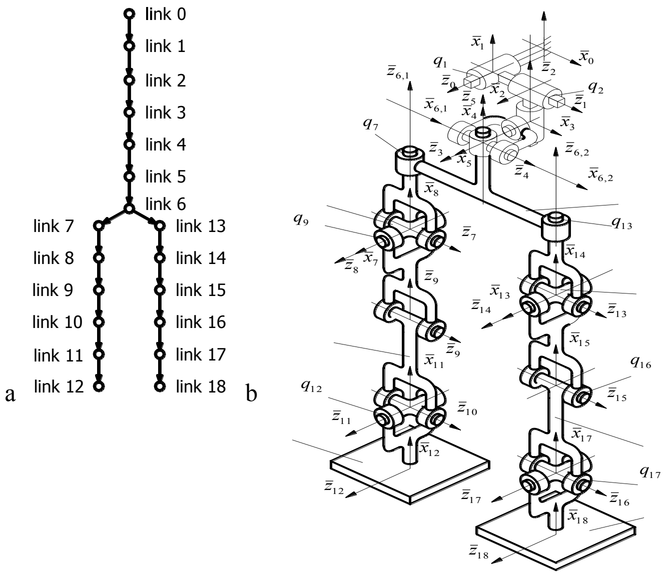


Fig. 2. (a) the corresponding treelike directed graph and (b) DSHR mechanism kinematic block diagram.

Block-matrices robots equations and equate methodology described in [4] has simple open kinematic circuit. Referring to reference [5] elements of graph theory are used and kinematic and dynamic equations are derived for the mechanism with branch kinematic chains. But this work does not contain final equation derivation for all mechanisms – mathematical model is described in terms of recurrence relations for every mechanism link.

Kinematic scheme of anthropomorphic DSHR's actuator is given as a tree directed graph (fig. 2). The mechanism links describes as the graph nodes, and its joints – as the arcs. An inertial space with its fixed coordinate system corresponds to a link numbered 0 (a root of the graph). Links numeration begins with 1 and rises without missing numbers from the root to the leaves. A generalized coordinate number, as its corresponding joint-number, is the same as the number of the link that connects this joint to its parent link.

In this article (for the description of the tree like mechanism) following functions and identifications, based on the graph theory terms, will be used:

$L = \{1,2,...N\}$ - Unordered set, which elements are the mechanism link numbers.

$f(i)$ – Returns number of the link, that is link-father for the link $i$, $i \in L$.

$s(i,k)$ – Returns number of the link, that is $k$-th link-son for the link $i$.

$dg^{+}(i)$ – $i$ th link out-degree, that defines amount of links-sons for $i$ link.

$ns(i)$ – Defines $i$ link-son number to its link-father (link-father enumerates its link-sons starting from 1 – every link-son has the number for its link-father).

$\sigma_i \in \{0,1\}$ - Coefficients, that defines type of joint between link $i$ and it's link-father, $\sigma_i = 1$ - matches to rotational joint type, $\sigma_i = 0$ - telescopic joint type.

Kinematic and dynamic equations in terms of mathematical model for the tree-like mechanism may be written by using the block matrix apparatus [4]. In this case, the tree-like mechanism's links relative positions are specified by the accessibility matrix. That is lower triangular matrix *D*. Each of its elements $d_{ij}$ equals to 1, if $i$ th node is accessible from a node *j*. For DSHR mechanism (fig. 2), its kinematic structure reachability matrix is as follows:

$$D_{18\times18} = \begin{pmatrix} U_{6\times6} & \Theta_{6\times6} & \Theta_{6\times6} \\ \mathrm{I}_{6\times6} & U_{6\times6} & \Theta_{6\times6} \\ \mathrm{I}_{6\times6} & \Theta_{6\times6} & U_{6\times6} \end{pmatrix},$$

where

$$U = \begin{pmatrix} 1 & 0 & ... & 0 \\ 1 & 1 & ... & 0 \\ ... & ... & ... & ... \\ 1 & 1 & ... & 1 \end{pmatrix}$$

is the lower triangular matrix, $u_{i,j} = 1$, $(i \geq j)$. I is the matrix, whose elements equal to 1. $\Theta$ is the zero matrix.

In general case every link of a tree-like mechanism has several fixed to these link coordinate systems, which amount is equal to the quantity of the link-sons for this link. The orts $\bar{z}_{ik}$ sequence for all fixed-to-links coordinate systems (for the mechanism's matrix mathematical model) is written as block vector $\mathbf{z} = (\bar{z}^T_{f(1),ns(1)}\ \bar{z}^T_{f(2),ns(2)}\ ..\ \bar{z}^T_{f(N),ns(N)})^T$, and the joint type (type of the links connection) is described by a $\boldsymbol{\sigma} = diag(\sigma_1\ \sigma_2\ ...\ \sigma_N)$ matrix. In this expressions N is the number of mechanism's links.

Such robot's kinematic structure formulation for the tree-like mechanisms may be used for the mathematical notation of all robot's links kinematic and dynamic relation. Moreover, the mathematical notation takes the form of analogical mathematical relations for the simple kinematic structures, which are described in details in [4]. Thus, expression for the block vector – an mechanism's links centers of mass acceleration is given by:

$$\mathbf{a}_{\ddot{o}i} = \left(D\cdot\mathbf{z}^d\cdot(E-\boldsymbol{\sigma})+\Lambda^T(\mathbf{c}_{fD})\cdot\mathbf{z}^d\cdot\boldsymbol{\sigma}\right)\cdot\ddot{\mathbf{q}}+\Lambda^T(\mathbf{c}_{fD})\cdot\Lambda^T(\cdot\mathbf{z}^d\cdot\boldsymbol{\sigma}\cdot\dot{\mathbf{q}}^d)\cdot(D-E)\cdot\mathbf{z}^d\cdot\boldsymbol{\sigma}\cdot\dot{\mathbf{q}}+$$
$$+\Lambda^T\cdot(\Lambda^T(\mathbf{c}_{fD})\cdot\boldsymbol{\sigma}\cdot\dot{\mathbf{q}}^d\cdot\mathbf{z}^d\cdot D+\Lambda^T(\mathbf{c}_{fD})\cdot\left((D-E)\cdot\boldsymbol{\sigma}\cdot\mathbf{z}^d\cdot\dot{\mathbf{q}}\right)^d)\cdot\mathbf{z}^d\cdot\boldsymbol{\sigma}\cdot\dot{\mathbf{q}}+$$
$$+2\cdot D\cdot\Lambda^T\left(\mathbf{z}^d\cdot(E-\boldsymbol{\sigma})\cdot\dot{\mathbf{q}}^d\right)\cdot(D-E)\cdot\mathbf{z}^d\cdot\boldsymbol{\sigma}\cdot\dot{\mathbf{q}}, \qquad (1)$$

To equate the actuator's forces and torques, the equations for the forces and torques, which acts on the $i$ links from the side of the $f(i)$ links should be projected on an axis $\bar{z}_{f(i),ns(i)}$.

Actuators strengths may be expressed in terms of the generalized coefficients and its derivatives. After we collect the coefficients at $\dot{q}$ and $\ddot{q}$, dynamic equation for the robots mechanisms with tree-like kinematic structures may be achieved according the joint reach-ability matrix *D*, block vector **z** and diagonal matrix $\sigma$:

$$A(\mathbf{q})\cdot\ddot{\mathbf{q}}+B(\mathbf{q},\dot{\mathbf{q}})-C(\mathbf{q})\cdot\mathbf{f}_в-H(\mathbf{q})\cdot\mathbf{n}_в=\boldsymbol{\tau}, \qquad (2)$$

where:

$$A(\mathbf{q})=\sigma\cdot\left(\mathbf{z}^d\right)^T\cdot(-\left(\Lambda(\mathbf{c}_{fD})\right)^T\cdot\mathbf{m}^d\cdot(D\cdot\mathbf{z}^d\cdot(E-\boldsymbol{\sigma})++\Lambda^T(\mathbf{c}_{fD})\cdot\mathbf{z}^d\cdot\boldsymbol{\sigma})+D^T\cdot\mathbf{J}_C^d\cdot D\cdot\mathbf{z}^d\cdot\boldsymbol{\sigma})+$$
$$+(E-\sigma)\cdot\left({}^0\mathbf{z}^d\right)^T\cdot D^T\cdot\mathbf{m}^d\cdot(D\cdot{}^0\mathbf{z}^d\cdot(E-\boldsymbol{\sigma})+\Lambda^T({}^0\mathbf{c}_{fD})\cdot{}^0\mathbf{z}^d\cdot\boldsymbol{\sigma}); \qquad (3)$$

$$B(\mathbf{q},\dot{\mathbf{q}})=\sigma\cdot\left(\mathbf{z}^d\right)^T\cdot\left\{-\left(\Lambda(\mathbf{c}_{fD})\right)^T\cdot\mathbf{m}^d\cdot\left[\Lambda^T(\mathbf{c}_{fD})\cdot\cdot\Lambda^T(\mathbf{z}^d\cdot\boldsymbol{\sigma}\cdot\dot{\mathbf{q}}^d)\cdot(D-E)+\right.\right.$$
$$+\Lambda^T(\Lambda^T(\mathbf{c}_{fD})\cdot\boldsymbol{\sigma}\cdot\dot{\mathbf{q}}^d\cdot\mathbf{z}^d\cdot D+\Lambda^T(\mathbf{c}_{fD})\cdot\left((D-E)\cdot\boldsymbol{\sigma}\cdot\mathbf{z}^d\cdot\dot{\mathbf{q}}\right)^d)+$$
$$\left.+2\cdot D\cdot\Lambda^T\left(\mathbf{z}^d\cdot(E-\boldsymbol{\sigma})\cdot\dot{\mathbf{q}}^d\right)\cdot(D-E)\right]+D^T\cdot\mathbf{J}_C^d\cdot D\cdot\boldsymbol{\sigma}\cdot\dot{\mathbf{q}}^d\cdot\Lambda^T(\mathbf{z}^d)\cdot(D-E)+D^T\cdot\Lambda\left(D\cdot\mathbf{z}^d\cdot\boldsymbol{\sigma}\cdot\dot{\mathbf{q}}\right)^d\cdot$$
$$\left.\cdot\mathbf{J}_C^d\cdot D\right\}\cdot\mathbf{z}^d\cdot\boldsymbol{\sigma}\cdot\dot{\mathbf{q}}+(E-\sigma)\cdot\left({}^0\mathbf{z}^d\right)^T\cdot D^T\cdot\mathbf{m}^d\cdot\cdot\left[\Lambda^T({}^0\mathbf{c}_{fD})\cdot\Lambda^T({}^0\mathbf{z}^d\cdot\boldsymbol{\sigma}\cdot\dot{\mathbf{q}}^d)\cdot(D-E)+\right.$$
$$+2\cdot D\cdot\Lambda^T\left(\mathbf{z}^d\cdot(E-\boldsymbol{\sigma})\cdot\dot{\mathbf{q}}^d\right)\cdot(D-E)+\Lambda^T\cdot(\Lambda^T(\mathbf{c}_{fD})\cdot\boldsymbol{\sigma}\cdot\dot{\mathbf{q}}^d\cdot\mathbf{z}^d\cdot D+\Lambda^T(\mathbf{c}_{fD})\cdot$$
$$\left.\cdot\left((D-E)\cdot\boldsymbol{\sigma}\cdot\mathbf{z}^d\cdot\dot{\mathbf{q}}\right)^d)\right]\cdot\mathbf{z}^d\cdot\boldsymbol{\sigma}\cdot\dot{\mathbf{q}}; \qquad (4)$$

$$C(\mathbf{q})=\boldsymbol{\sigma}\cdot\left(\mathbf{z}^d\right)^T\cdot\left(\left(D^T-E\right)\cdot\Lambda(\mathbf{s}^d)\cdot D^T+D^T\cdot\Lambda(\mathbf{t}^d)\right)+(E-\boldsymbol{\sigma})\cdot\left(\mathbf{z}^d\right)^T\cdot D^T; \qquad (5)$$

$$H(\mathbf{q})=\boldsymbol{\sigma}\cdot\left(\mathbf{z}^d\right)^T\cdot D^T. \qquad (6)$$

In this mathematical expression:

$\mathbf{m}$, $J_C$, $c_{fD}$, $t^d$ are block matrices which specify weight-and-dimensional characteristics of the mechanism with tree-like kinamatic structure. $\tau$ is the vector of generated hydraulic efforts. $\mathrm{f}_в$ and $n_в$ are the block vectors of external forces and torques, which act on the mechanism.

DSHR block vectors $\mathrm{f}_в$ and $n_в$ are defined by mathematical modeling of robot's foots elastic elements deformation during its walking. Efforts $\tau$ are evaluated by robot's electro hydraulic drives modeling for the mechanism.

## 3. Robot's dynamic equation in case of tree-like kinematic structure and kinematic constraints

The robot mechanism interacts with an environment during its walk. In general case robots are able to interact with a support surface through a stationary column (the mounted manipulator), through the chassis's elements (manipulators installed at a wheeled/track-laying machine), through the supporting elements, which are installed at the certain mechanism's elements (walking robots). Besides, the situations must be examined when a robot interacts with the elements, which are stationary relative the environment (for example, an interaction between a manipulator and the work-pieces to be processed/assembled). In any case mentioned an mechanism motion is defined not only by mechanism's dynamic, but also by the forces constrained.

The applied constraints are resulted in additional equation components caused by constraints forces and torques. As a result, an equation (2) is written as:

$$A(\mathbf{q})\cdot\ddot{\mathbf{q}} + B(\mathbf{q},\dot{\mathbf{q}}) - L(\mathbf{q})\cdot\mathbf{F}_{в} - L_R(\mathbf{q})\cdot\mathbf{R} = \boldsymbol{\tau}, \qquad (7)$$

where

$\mathbf{F}_{\hat{a}} = (\mathbf{f}_{\hat{a}}^T \quad \mathbf{n}_{\hat{a}}^T)^T$ is a block vector for external forces and torques, applied to the links of the mechanism ($\mathbf{f}_{\hat{a}}$ are the external forces and $\mathbf{n}_{\hat{a}}$ are the external torques). $\mathbf{R} = \left(\mathbf{R}_f^T \quad \mathbf{R}_n^T\right)^T$ is a block vector for mechanism constraint reaction ($\mathbf{R}_f$ are the external reaction forces and $\mathbf{R}_n$ are the external reaction torques).

$L(\mathbf{q}) = \left(\tilde{N}(\mathbf{q}) \quad H(\mathbf{q})\right)$ is Jacobean matrix, combined with external forces $\tilde{N}(\mathbf{q})$ and torques $H(\mathbf{q})$ matrix coefficients (the forces and torques acts on the mechanism links),

$L_R(\mathbf{q}) = \left(\tilde{N}_R(\mathbf{q}) \quad H_R(\mathbf{q})\right)$ is Jacobean matrix, combined with constraint matrix force $\tilde{N}_R(\mathbf{q})$ and torque $H_R(\mathbf{q})$ coefficients (the constraint forces and torques applied to the mechanism links).

The kinematic constraints expressions for the mechanism may be written in a following matrix form:

$$J_t \cdot \ddot{\mathbf{q}} + \mathbf{P} = 0, \qquad (8)$$

where matrices $J_t$ and $\mathbf{P}$ are defined by the equations derivation for holonomic and nonholonomic constraints.

Equation (8) defines the kinematic constrains imposed on the mechanism's significant points movement. For an mechanism to move in such constraints, the matched environment-side efforts should be applied – constrained forces $\mathbf{R}$.

Having connected equations (7) and (8) we got dynamic equation for one block matrix mechanism for tree-like kinematic structure and some movement under kinematic constrains:

$$\begin{pmatrix} A(\mathbf{q}) & -\tilde{N}_R(\mathbf{q}) \\ J_t(\mathbf{q}) & 0 \end{pmatrix} \cdot \begin{pmatrix} \ddot{\mathbf{q}} \\ {}^0\mathbf{R}_f \end{pmatrix} + \begin{pmatrix} B(\mathbf{q},\dot{\mathbf{q}}) \\ \mathbf{P}(\mathbf{q}) \end{pmatrix} - \begin{pmatrix} L(\mathbf{q})\cdot\mathbf{F}_{\hat{a}} \\ 0 \end{pmatrix} = \begin{pmatrix} \boldsymbol{\tau} \\ 0 \end{pmatrix} \qquad (9)$$

Where $J_t(\mathbf{q})$ is the Jacobean matrix, that defines kinematical relations, restricted by links. $C_R(\mathbf{q})$ is the transposed Jacobean matrix, that defines mechanism kinematical constrains.

## 4. DSHR hydraulic drive's mathematical modeling

DSHR is equipped with EHSD, that tracks required positions (fig. 3). A hydraulic drive is controlled by a two-stage electro hydraulic amplifier (EHA). At the first amplifying stage an electromechanical converter (flapper-nozzle type) is used. At the second stage cylindrical control valve is used. All EHSD are connected to one hydraulic power unit, placed at the DSHR body.

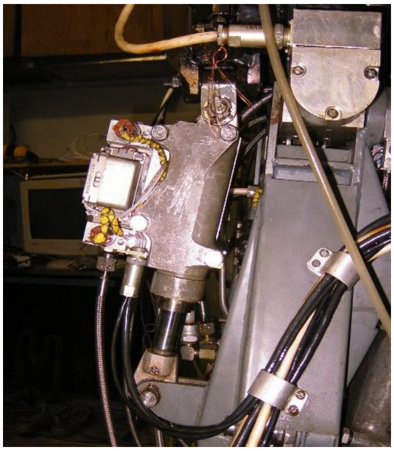

Fig. 3. EHSD appearance.

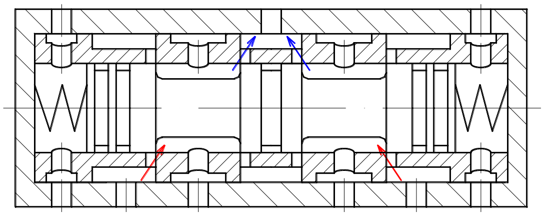

Fig. 4. A spool-valve construction arrangement.

EHSD's nonlinear mathematical model was designed referred to methodic and assumption described in [6,7] (considering actuating fluid compressibility, pressure/flow characteristic curve nonlinearity of electro hydraulic amplifier, cavitation possibility, etc.).

During a motion along the mechanical trajectory DSHR's EHSD works in smaller control signals amplitude area. Thus actuating fluid flow modeling has a particular importance, in a case of fluid flowing through a hydraulic distributor at small spool-valve shift. A Mathematical model that defines fluid flow-rate through the spool-valve (fig. 4, 5) is formulated according to the methods contained in [8]. The referred methods describe spool-valve characteristics at «zero-area».

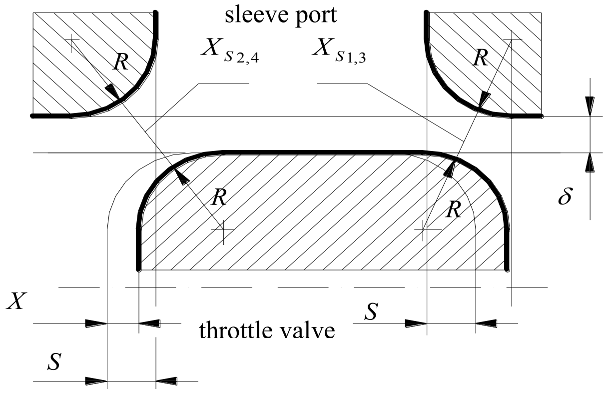


Fig. 5. The throttle gap geometry variables.

Thus the flow-rates were modeled through the four spool-valve's throttle gaps.

$$Q_i = a_S \cdot X_{S_i} \cdot \sqrt{p_{in_i} - p_{out_i}}\,, \tag{10}$$

where $i = 1..4$ is a number of the throttle gap agreed notation, $a_s$ is the coefficient determined by the coefficient of discharge, the gap width at the spool edge, and by the actuating fluid density. $X_{si}$ is the throttle gap value. $p_{ini}$, $p_{outi}$ are the throttle gap inlet and outlet pressure values correspondingly.

The parameters that define the spool-valve micro-geometry are shown in fig. 5. $R$ is the edge radius. $S$ is the spool-valve positive overlap value. $\delta$ is the radial clearance between the sleeve and the spool. $X_{si}$ as a function of the spool-valve shift $X$ is shown in fig. 6 and is conditioned by the spool-valve micro-geometry.

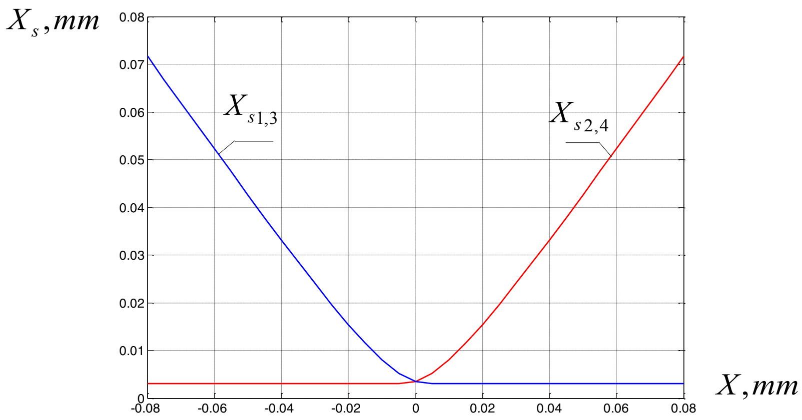


Fig. 6. Dependence of the spool valve gap value (for a hydraulic valve) from the spool displacement.

The micro-geometrical parameters of the spool-valve's mathematical model were specified in [8] and revised in [9] numerically.

## 5. Experiment

The DSHR's program trajectory was set as the input signal of both the control system incorporated with the DSHR's mathematical model and the control system incorporated with the DSHR's mechanism. It was done for the quality research of the DSHR's mathematical model. Fig. 7 and 8 shows required and measured DSHR mechanism state variables of orthogonal coordinates during DSHR walking (mathematical modelling and natural experimental results comparison).

Research has shown good accordance of the DSHR's mathematical model solution with the DSHR's mechanism behaviour. This has made it possible to tune DSHR's stable walking trajectory parameters on the mathematical model during intermediate research. Thus the DSHR's mechanism fallings were excluded. The walking trajectory quality was measured as error angle for DSHR's body. Figures 7 and 8 show that maximum DSHR's body angle error is less than 1.5 degree. That provides robot's walking stability.

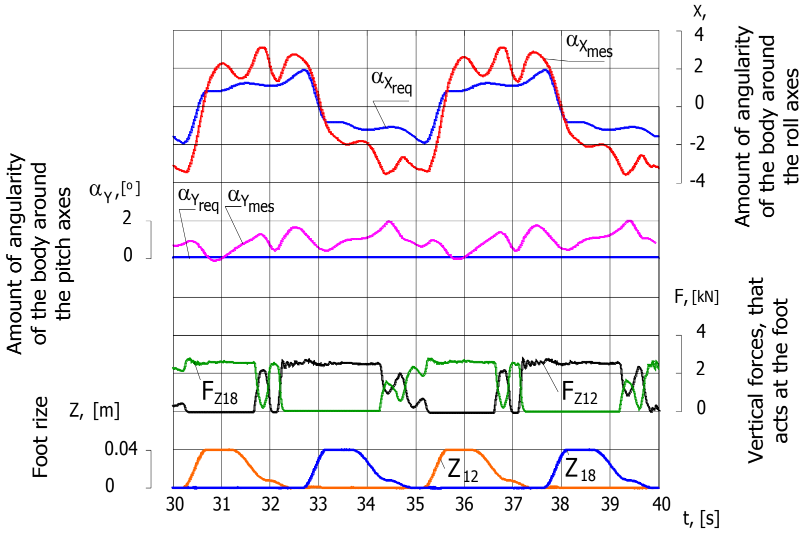


Fig. 7. DSHR walking modeling.

The notation conventions for fig. 6 & 7:

$Z_{12}$, $Z_{18}$ - right and left robot's foot rise height program values;

$F_{Z12}$, $F_{Z18}$ - vertical forces at right and left foot during a walking;

$\alpha_{X\,req}$, $\alpha_{Y\,req}$ - program amount of angularity of the body around the axes X and Y;

$\alpha_{X\,mes}$, $\alpha_{Y\,mes}$ - measured amount of angularity of the body around the axes X and Y.

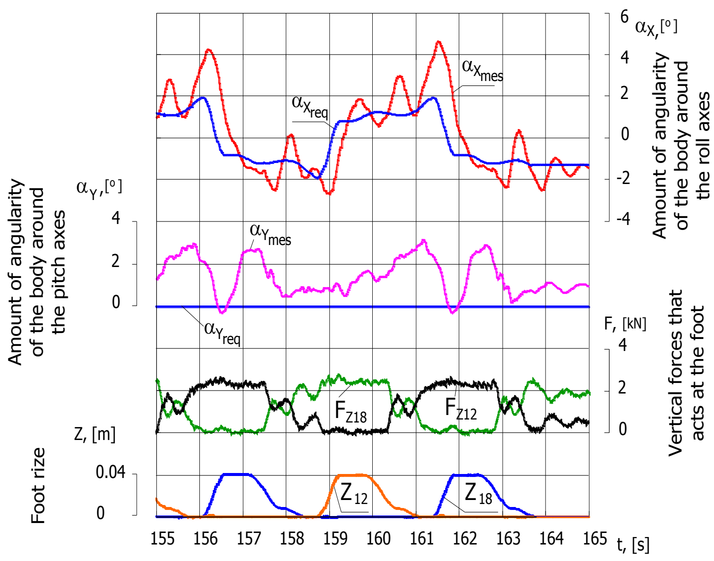


Fig. 8. DSHR experimental walk.

## 6. Conclusion

Developed mathematical model accuracy is confirmed by practical matching of experimental and mathematical model results of walking DSHR.

Achieved motion equation for robots mechanisms that is determined by block-matrices apparatus can be used in mathematical modeling of a mechanisms motion with different tree-like kinematic structures. An accessibility matrix defines a robot's kinematic scheme in a block-matrix motion equation which leads to great software flexibility for retuning parameters to a different robot case. It was used in the universal computer program developed for a walking robots mechanism modeling. Creating a new robot's mathematical model comes down to the inputs of the new matrices (mass and inertia parameter matrices, matrix defining geometrical parameters, reachability matrix) to the existing computer program. After that the program becomes the modelling program for our mechanism.

The developed mathematical model of the DSHR with EHSD mechanism can be used at DSHR trajectory optimization process, as well as the EHSD and pump unit parameters definition, for the DSHR movement along the synthesized trajectory.

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